

## REVIEW ARTICLE

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## High-temperature wear of cemented tungsten carbide tools while machining particleboard and fiberboard

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**Abstract** Published research on the wear processes of cemented tungsten carbide tools used for machining reconstituted wood products was reviewed, and the current state of knowledge in this area was evaluated. Underlying assumptions and conclusions regarding high-temperature oxidation/corrosion wear during machining were examined in view of known reaction kinetics of cemented tungsten carbide alloys in oxidative and corrosive environments at temperatures that may occur at the cutting edge. This examination indicated that some wear mechanisms other than high-temperature oxidation/corrosion are likely to be rate-controlling when machining reconstituted wood products such as particleboard and fiberboard.

**Key words** Cemented tungsten carbide · Machining · Wear mechanism · Particleboard · Fiberboard

### Introduction

Cemented carbide tools consist primarily of a large volume fraction of fine grain refractory metal carbide in a metal binder. Most cemented carbides are tungsten carbide-based with a cobalt binder (WC-Co). Cemented carbides are produced by cold pressing of powder mixtures of the refractory carbide grains and the metal binder, followed by liquid-phase sintering at temperatures in the range of about 1350°–1650°C, depending on composition.<sup>1</sup> Small amounts of other carbides such as titanium carbide (TiC) and tantalum carbide (TaC) may be added to improve wear resistance during the high-speed machining of steels and gray cast iron.

For almost three decades the use of cemented tungsten carbide cutting tools in the wood-working industry has provided significant improvements in tool life, primarily because of the superior hardness of these alloys compared to that of carbon steels, tool steels, and cast cobalt alloys (e.g., stellite). The improvement in tool life has been particularly significant in machining abrasive materials, such as silica-containing tropical wood species (e.g., melapi) and reconstituted wood products (e.g., particleboard and fiberboard). Cemented tungsten carbides are most commonly used in the wood-working industry as tipping material and inserts for circular saws and peripheral milling machines. Despite their wide use, little is known concerning their wear behavior, especially in the high-speed machining of reconstituted wood products.

During the cutting of wood and wood-based products, several wear mechanisms may simultaneously contribute to the general wear of the cutting tool. Among these wear mechanisms are gross fracture or chipping, abrasion, erosion, microfracture, chemical and electrochemical corrosion, and oxidation. Gross fracture results in the sudden or catastrophic failure of the cutting edge, whereas the other wear mechanisms result in gradual or progressive wear. Abrasion, erosion, and microfracture involve the mechanical removal of microscopic wear particles. Corrosion and oxidation involve chemical transformation of the tool material into compounds that can be easily removed from the cutting edge by abrasion. Depending on the cutting conditions (e.g., cutting speed, feed speed, chip thickness) and workpiece conditions (e.g., moisture content, composition) some of these mechanisms may play a dominant role and become rate-controlling.

Chemical and electrochemical corrosive wear of cemented tungsten carbide tools when machining green wood was investigated by Kirbach and Chow,<sup>2</sup> Bailey et al.,<sup>3</sup> Bayoumi et al.,<sup>4</sup> Bayoumi and Bailey,<sup>5,6</sup> and Murase.<sup>7</sup> It was concluded that wear takes place by preferential dissolution of the cobalt binder through chemical attack by the extractives present in green wood, which in turn leads to mechanical removal of the tungsten carbide grains. It was also concluded that resistance to corrosive wear is increased by

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adding chromium and nickel to the cobalt binder, by decreasing cobalt content, and by decreasing grain size. Kirbach and Bonac<sup>8</sup> compared the wear resistance of stellite, in which cobalt is alloyed with chromium, and tungsten carbide tips for sawing unseasoned redcedar. They found that stellite was more resistant to corrosive wear than some tungsten carbides containing a high percentage of cobalt binder. Mohan and Klamecki<sup>9</sup> measured the electrical potentials between components of cemented carbide tool in solutions derived from green wood and concluded that the electrochemical reactions can be influenced by changes in the binder composition, its weight percentage, and the carbide grain size. Murase<sup>7</sup> and Fukuda et al.<sup>10,11</sup> demonstrated that electrochemical wear of the tungsten carbide tool can be reduced by applying a negative electric potential between the cutting tool and the workpiece. By comparing edge wear for tools with and without negative electric potentials Fukuda et al.<sup>11</sup> were able to separate the mechanical and corrosive components of tool wear. It was reported that corrosive wear constitutes about 40%–65% of the total wear and that an increase in cobalt content and an increase in grain size leads generally to a proportional increase in corrosive wear.

The wear behavior of cemented tungsten carbides when machining reconstituted wood products is significantly different from that when machining green and dry solid wood. In general, reconstituted wood products are harder, more abrasive, and dryer than solid wood. Particleboard and fiberboard contain wood in the form of particles or fibers, bonding agents, fillers and extenders, and possibly silica. They machine mostly by fracture, and a continuous chip is seldom formed. The cutting temperatures are expected to be higher than when machining solid wood, and thermal decomposition of the board constituents may adversely affect tool wear by introducing reactive gases and vapors. Removal of the cobalt binder is also a characteristic appear-

ance of the wear surface of cemented tungsten carbide tools used when machining particleboard and fiberboard.<sup>12–18</sup> However, a clear understanding of the wear mechanisms involved in removing the binder has not yet been developed. The work in this field carried out to date has generated much controversy over the interpretation of experimental data, and there is no consensus as to the wear mechanisms involved.

The purpose of this study was to help clarify the nature of the wear processes occurring when cemented tungsten carbides are used for machining reconstituted wood products by reviewing critically some of the published work in this field. The various hypotheses and conclusions underlying the current understanding are examined in the light of known kinetics of the chemical reactions of cemented carbides in oxidative and corrosive environments at high temperatures. As knowledge of the cutting tool temperature is extremely important for developing a full understanding of tool wear mechanisms, this paper also includes a review of published work on temperature measurement during wood machining.

### Tool temperatures in wood cutting

The cutting edge temperature is one of the most important factors governing tool wear because critical tool material properties such as hardness, toughness, and chemical stability degrade with increasing tool temperatures. Thus, the contribution of the various wear mechanisms during wood cutting cannot be assessed without first having accurate information on tool edge temperature and how it affects the basic material properties of the cutting tool.

The temperature distribution near the tool edge during wood cutting has been investigated experimentally, analytically, and numerically.<sup>19–37</sup> Table 1 provides a summary of

**Table 1.** Summary of experimental work on cutting tool temperature for wood cutting

Ref.	Cutting process	Tool material	Measurement Method	Cutting speed (m/s)	Feed speed	Near edge temp. (°C)
19	Cutting by double arm pendulum	HSS sawtooth	TC at 0.55 mm from edge	15–32	0.2–1.2 mm	100–500
20	Sliding	Alloy tool steel, HSS, WC-Co	TC at 3, 5, 8 mm	1–5	–	40–200
21	Continuous orthogonal	HSS	TC at 4, 6, 9 mm	0.2–20	0.05 mm	20–200
22	Boring	HSS	TC at 0, 10, 20, 40 mm	505–1970 rpm	0.1, 0.3 mm/rev	100–250
23	Rubbing	Steel	TC 2, 4, 8, 16 mm	1.1–14	–	60–260
24	Continuous cutting on a lathe	WC-Co	TC at 1, 2, 3 mm	17.6–42	0.05, 0.1 mm/rev	200–275
25	Sawing	HSS	IR at 0.3 mm	57, 79	10, 15, 20 m/min	250–350
26	Rubbing on back face	WC-Co sawtooth	IR at 0.15 mm	1.6–23.6	–	120–250
27	Interrupted orthogonal cutting	WC-Co	IR at 0.11 mm	5–20	0.043 mm	50–154 <sup>a</sup>
28	Interrupted grooving	WC-Co	IR at 0.11 mm	5–20	0.043 mm	100–200 <sup>a</sup>
29	Peripheral milling	Alloy tool steel, HSS	Microhardness	22–45	1 mm feed/tooth	200–310 <sup>a</sup>
30	Peripheral milling	HSS, stellite	Microhardness	44 25	–	375 <sup>a</sup> 550
31	Boring	HSS	Microhardness	31.4–188.5	0.1 mm/rev	100–460 <sup>a</sup>
32	Interrupted edge cutting	WC-Co	PVD film	26.5–30.5	0.35 mm	327 <sup>a</sup>

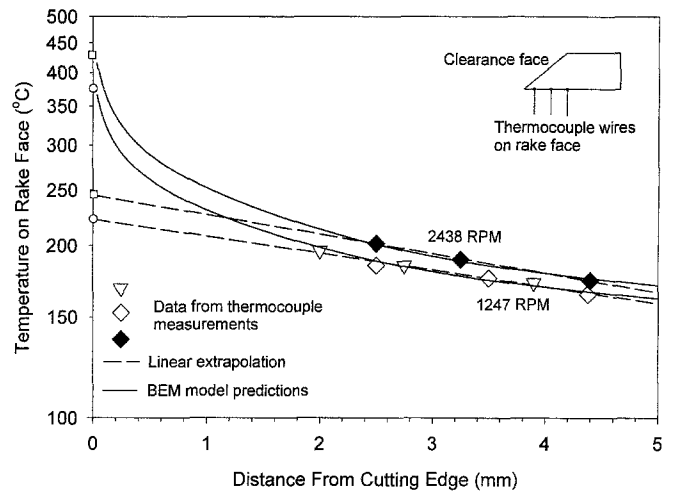
TC, thermocouple wires embedded in or bonded to the surface of the tool; IR, infrared radiometric microscope, spot size 0.05 mm or less; WC-Co, tungsten carbide based with a cobalt binder; HSS, high speed steel

<sup>a</sup>Peak temperatures

the findings of some experimental work conducted in this area. Temperatures close to the cutting edge have been measured using thermocouples,<sup>19–24</sup> infrared radiometry,<sup>25–28</sup> and thermomechanical<sup>29–31</sup> and thermochemical<sup>32</sup> techniques. In some cases, measurements close to the edge have been extrapolated on a semilog scale to estimate the cutting edge temperature.<sup>20–24</sup> Thus, the temperatures reported in Table 1 may represent only lower limits of the cutting edge temperature; the actual cutting edge temperature may be significantly higher. Temperature measurements based on infrared radiometry and microhardness information were often determined as close as 0.1 mm to the cutting edge.<sup>25–31</sup>

The cutting edge temperature is dependent on several factors, such as cutting speed, feed speed, continuity of the cutting process, depth of the cut, and tool and workpiece materials. Cutting speed is by far the most important factor influencing cutting tool temperature. Inoue,<sup>21</sup> Okumura and Sugihara,<sup>26</sup> and Banshoya and Fukui<sup>31</sup> have shown that cutting tool temperature varies with cutting speed according to a power law relation. Chardin<sup>19</sup> and Okushima et al.<sup>25</sup> reported that an increase in feed speed (chip thickness) resulted in an increase in cutting tool temperature. This, however, was in contrast to the findings of Okumura et al.,<sup>22</sup> who reported that cutting tool temperatures while boring decreased with an increase in feed speed. The interrupted nature of the chip removal process in most wood machining operations introduces a periodic component into the temperature variation with time. This is most pronounced in a small zone at the cutting edge where the contact time is short and the heat due to cutting is applied repeatedly at a high frequency. Zones of the cutting tool far away from the cutting edge (more than 1.0 mm) experience only a gradual increase in temperature.<sup>19,27,28</sup>

A few researchers have attempted to determine the cutting tool temperature theoretically. In this work the accuracy of the theoretical solution depends greatly on the underlying assumptions concerning boundary conditions and the proportion of the cutting energy that is converted to heat at the tool–workpiece interface. Okushima and Sugihara<sup>33</sup> used the finite difference method to calculate the temperature of a wood cutting tool under steady-state conditions. In this work the authors adopted the well known analytical model of Lowen and Shaw<sup>34</sup> for metal machining to calculate the proportion of cutting energy that flows into the tool as heat. It was predicted that temperatures of the order of 500°C occur at the cutting edge when cutting at 40 m/s, but no comparisons were made with experimental results. Okumura<sup>35</sup> obtained the transient temperature in the cutting edge by treating the problem as one-dimensional heat conduction in cylindrical coordinates. It was assumed that the cutting edge was insulated on both sides and that heat generation takes place at the cutting edge. The proportion of heat that flows into the tool was chosen arbitrarily. It was shown that under interrupted cutting conditions significant changes in temperature occur in an area less than 0.5 mm from the cutting edge. This was in qualitative agreement with the previous experimental work by Okumura et al.<sup>27,28</sup> Csanady<sup>36</sup> has investigated the transient temperature distribution in peripheral milling using the finite element



**Fig. 1.** Temperature distribution on the rake face of a cutting tool as determined experimentally and by the boundary element method (BEM)<sup>37</sup>

method. It was predicted that instantaneous temperatures of the order of 900°–1000°C may occur at the cutting edge for a short period of time, but no experimental verification was given. Lewandowski<sup>37</sup> solved the steady-state heat conduction problem in the cutting tool using the boundary element method. In this treatment the proportion of heat conducted into the tool was chosen such that the temperatures on the face and back of the tool would match experimentally measured values. Typical temperature distributions on the rake face of the tool, as determined by the boundary element method (BEM), are shown in Fig. 1.<sup>37</sup> Figure 1 also shows temperature measurements obtained using thermocouple wires bonded to the rake face of the tool. It shows that temperatures in the vicinity of 430°C are predicted near the cutting edge when a 381 mm diameter particleboard disk was continuously machined on a lathe at an average cutting speed of 38 m/s (2430 rpm) and a feed speed of 0.05 mm/rev. Comparison with cutting edge temperatures obtained by linear extrapolation on a semilog scale indicated that the temperatures obtained by the BEM model are approximately 150°C higher than those obtained by linear extrapolation.

### Oxidation kinetics of cemented tungsten carbides

High-temperature properties and chemical stability of cemented tungsten carbides are of great importance because many of the applications of these alloys as cutting tools involve high temperatures. During machining of particleboard and fiberboard, the tool material is exposed to reactive gases and vapors generated from thermal decomposition of wood fibers and other board additives at high temperatures. The presence of these reactive agents may adversely affect tool wear. Therefore, an understanding of the chemical reactions of WC-Co alloys in air and in the presence of manmade wood products at high temperatures

is important. This section presents a review of work conducted on the oxidation kinetics of the WC-Co alloys in oxidative and reactive environments.

#### Oxidation of cemented tungsten carbides in air

The oxidation behavior of WC-Co alloys in air has been studied by many investigators.<sup>38-47</sup> It was found that the reactions for these alloys are most likely described by



and result in gaseous products, namely  $\text{CO}_2$  and  $\text{WO}_3$ , which evaporates at temperatures above  $800^\circ\text{C}$ . This makes evaluation of the oxidation kinetics based on weight gain measurement misleading. For example, Kieffer and Kölbl<sup>38</sup> investigated the oxidation of a WC-6Co alloy and reported a weight gain of 0.066% after heating for 1 h at  $700^\circ\text{C}$ . Dawihl<sup>39</sup> carried out similar experiments but removed the scale by brushing prior to weighing. He reported a weight loss of  $0.11 \text{ g cm}^{-2} \text{ h}^{-1}$  for the same alloy at  $700^\circ\text{C}$ .

Gumnitskii et al.<sup>40</sup> investigated the oxidation kinetics of a WC-8Co alloy in air at temperatures from  $700^\circ$  to  $1050^\circ\text{C}$ . They reported that the oxidation rate at  $700^\circ\text{C}$  was insignificant but became high in the temperature range  $900^\circ$  to  $1000^\circ\text{C}$ . The oxide layer at the surface of specimens consisted mainly of  $\text{WO}_3$  and  $\text{CoO}$ . Traces of other tungsten oxides such as  $\text{WO}_2$  and  $\text{W}_{18}\text{O}_{49}$  were also found below the surface. Larikov et al.<sup>41</sup> investigated the oxidation kinetics of WC-Co alloys of different compositions and porosity in the temperature range from  $700^\circ$  to  $1000^\circ\text{C}$  in air. They found that the increase in weight for these alloys obeyed a parabolic law. The rate constant at  $780^\circ\text{C}$  for the alloy WC-6Co with 15% porosity was  $760 \text{ g}^2 \text{ m}^{-4} \text{ s}^{-1}$ . An increase in Co content from 4% to 8% was reported to cause a significant decrease in the oxidation rate. The oxide layer was identified as  $\text{WO}_3$  on the surface and a mixture of  $\text{WO}_3$  and  $\text{WO}_2$  below the surface. Lofaj and Kaganovskii<sup>42</sup> investigated the oxidation kinetics of WC-Co alloys with a 3- to  $5\text{-}\mu\text{m}$  grain size and 6%–15% Co content, heated in air over a temperature range from  $650^\circ$  to  $800^\circ\text{C}$ . The rate of weight gain also followed a parabolic law in this work. In contrast to the findings of Larikov et al.<sup>41</sup> mentioned above, the oxidation rate increased with a decrease in grain size and an increase in cobalt content. The oxidation layer consisted mainly of  $\text{WO}_3$  and small amounts of  $\text{Co}$ ,  $\text{CoO}$ , and  $\text{WC}$ . An increase in the oxidation rate with a decrease in grain size and a decrease in cobalt content was reported by Reid et al.<sup>43</sup> when a WC-6Co alloy was heated in air at  $650^\circ\text{C}$ . Basu and Sarin<sup>44</sup> investigated the oxidation behavior of WC-Co alloys as a function of cobalt content, temperature, and the flow rate and oxygen concentration of the oxidizing atmosphere. It was reported that the oxidation rate of WC-Co increased rapidly at temperatures above  $600^\circ\text{C}$  and with the oxygen concentration of the atmosphere. An increase in the cobalt content of the alloy led to a decrease in the oxidation rate. The only oxides identified in the scale were  $\text{WO}_3$  and  $\text{CoWO}_4$ .

Kieffer and Kölbl<sup>38</sup> and Dawihl<sup>39</sup> have reported improvements in the oxidation resistance of WC-Co alloys due to the presence of other carbides. They demonstrated that the addition of  $\text{TiC}$  to a WC-Co alloy improves oxidation resistance. Bhaumik et al.<sup>45</sup> also showed that the addition of either  $\text{TiC}$  or  $\text{TiN}$  would enhance the oxidation resistance of a WC-10Co alloy, although the effect of  $\text{TiN}$  was more pronounced. The addition of  $\text{Mo}_2\text{C}$  increased the oxidation rate in this study.<sup>45</sup> Results on the effect of alloying elements such as nickel, chromium, and molybdenum on oxidation resistance are conflicting. The effect of adding corrosion-resistant elements to the Co binder was shown to have no significant effect on the oxidation rate of a WC-6Co alloy heated in air at  $650^\circ\text{C}$ ,<sup>43</sup> whereas the addition of Ni to the Co binder was shown to slightly reduce the oxidation rate.<sup>45</sup> Oakes<sup>46</sup> investigated the effect of adding Cr and Mo on the oxidation behavior of WC-Co-Ni alloys. He reported that adding about 5% Cr significantly improved oxidation resistance and that the addition of Mo reduced it. Voitovich et al.<sup>47</sup> investigated the oxidation behavior of WC-Co, WC-Co-Ni, and WC-Ni alloys in the temperature range from  $500^\circ$  to  $800^\circ\text{C}$  and found that the oxidation resistance was highest for the WC-Co alloy, followed by the WC-Co-Ni alloy and the WC-Ni alloy. This was attributed to the fast formation of a protective layer of the complex oxide  $\text{CoWO}_4$  as compared to the porous  $\text{WO}_3$  oxide and the slow formation of  $\text{NiO}$  and  $\text{NiWO}_4$  in the case of the WC-Ni alloy.

#### Oxidation and corrosion of cemented tungsten carbides in the presence of particleboard and fiberboard

The oxidation/corrosion behavior of WC-Co alloys at high temperatures and in the presence of particleboard and fiberboard chips has been reported in a few studies. Stewart et al.,<sup>15</sup> Reid et al.,<sup>43</sup> and Padilla et al.<sup>48</sup> performed thermal gravimetric analysis (TGA) on WC-6Co blanks heated at temperatures from  $500^\circ$  to  $1100^\circ\text{C}$  with and without the presence of medium density fiberboard (MDF) chips, and with the presence of other reactive agents such as alumina and  $\text{Na}_2\text{SO}_4$ . The TGA was performed at these temperatures based on the assumption that such temperatures may occur at the cutting edge during machining MDF. The heating time varied from several minutes to several hours. Results from the TGA showed that no noticeable weight gain (oxidation) of the tungsten carbide blanks occurred at temperatures below  $600^\circ\text{C}$ , with or without the presence of MDF chips, and that the weight gain became noticeable only at temperatures above  $700^\circ\text{C}$ .<sup>48</sup> The presence of MDF delayed the onset of oxidation until after 14 h at  $550^\circ\text{C}$  and until after 1 h at  $650^\circ\text{C}$ , but it has little effect at higher temperatures.<sup>48</sup> It was also reported that the presence of moisture in the MDF caused no significant change in the weight of the carbide sample at  $775^\circ\text{C}$  but caused a slight weight loss at  $1000^\circ\text{C}$ . The presence of  $\text{Na}_2\text{SO}_4$  caused significant weight loss with time at all temperatures.<sup>15</sup> Energy dispersive spectral analysis (EDS) of the scale formed on the surface of WC-6Co heated at  $650^\circ\text{C}$ , with and

without the presence of MDF chips, showed a higher concentration of cobalt than the parent material. This was interpreted to be a result of the partial vaporization of tungsten oxides.<sup>48</sup> It was postulated, based on these findings, that the peripheral oxidation of cobalt and the vaporization of tungsten oxides at temperatures above 600°C are the primary cause of the high temperature wear of WC-6Co tools while machining MDF.

High-temperature oxidation experiments were also conducted by Porankiewicz,<sup>49</sup> Porankiewicz et al.,<sup>50</sup> and Porankiewicz and Wagner.<sup>51</sup> Differential thermal analysis (DTA) of WC-6Co samples continuously heated in the presence of melamine-coated particleboard (MCPB) chips showed that exothermic peaks occurred at temperatures in the range of 424°–537°C.<sup>50</sup> Exothermic peaks occurred at 440°C and 424°C when cobalt powder was continuously heated in the presence of MDF and MCPB, respectively. However, no exothermic peaks were noted when WC powder was heated continuously to 500°C in the presence of MCPB.<sup>50</sup> The exothermic peaks observed in these experiments were interpreted mainly to be a result of the oxidation of cobalt powder to CoO and Co<sub>3</sub>O<sub>4</sub>. It was noted, however, that oxidation of cobalt powder also takes place at these peaks in ambient air and without the presence of thermal decomposition products from MCPB.<sup>51</sup> This makes it difficult to determine the exact effect of thermal decomposition products of reconstituted wood products on the oxidation kinetics of cemented tungsten carbides. In a related study, Dziembaj et al.<sup>52</sup> held preheated samples of WC-6Co in an atmosphere of gaseous products of the melamine laminate thermal decomposition at 300°C in air for 30 min. In this study, the presence of traces of W<sub>18</sub>O<sub>49</sub> was detected on the surface of the tool using X-ray photoelectron spectroscopy (XPS). Because oxidation of WC-Co in air occurs at temperatures much higher than 300°C, it was assumed that these oxides formed because of the corrosive effect of the melamine decomposition gases on the WC-Co alloy.

It is noted here that TGA and DTA techniques are not capable of identifying the presence of cobalt or tungsten oxides on the surface of worn cutting edge.<sup>53</sup> Recordings of weight changes in TGA and temperature changes in DTA may indicate the occurrence of oxidation, but no information can be obtained about which component of the WC-Co alloy is oxidizing and what is the stoichiometry of the reactions. Other analytical techniques such as X-ray diffraction and XPS can be used to characterize the chemical compounds of the sample, but these techniques were not used in most of the work presented above. In addition, information concerning the oxidation kinetics of cemented tungsten carbides as obtained from TGA and DTA may have little value in tool wear research, as it does not pertain to actual wood cutting conditions. For example, some of the results of TGA and DTA analyses came from experiments conducted at temperatures that appear to be well beyond those measured during wood cutting, as shown in Table 1. Also, the contact times in these experiments were much longer than those seen during actual cutting tests. In a typical wood cutting operation with an 180-mm cutterhead rotating at 6000 rpm

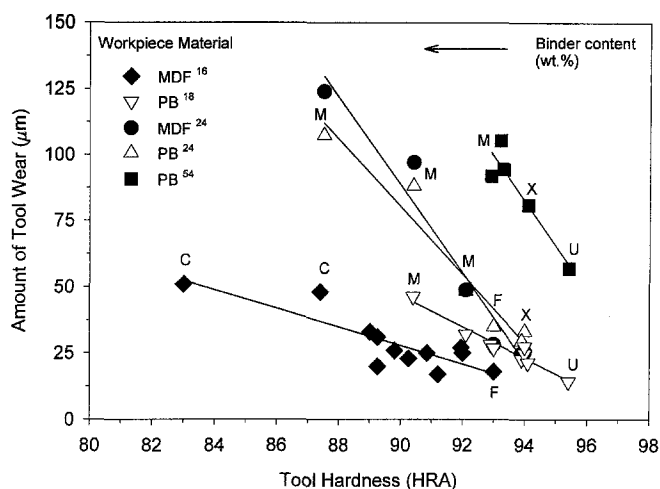
and taking a 2.0-mm cut, the contact time between the tool edge and the workpiece is approximately 0.3 ms. The cutting edge temperature may rise significantly for only a fraction of this time,<sup>27,28,36</sup> and then the cutting edge cools rapidly as it passes through air. Therefore, the oxidation/corrosion rates should be extremely fast for any significant material removal by oxidation/corrosion to occur during wood cutting.

### **Wear of cemented tungsten carbide tools in machining particleboard and fiberboard**

The work reviewed in this section addresses the issue of tool wear while machining particleboard and fiberboard. Emphasis is placed on elucidating the wear phenomenon and identifying the controlling wear mechanisms. Knowledge of the controlling wear processes while machining particleboard and fiberboard would eventually lead to making better choices of tool materials, the development of new tool materials, and improved wear resistance of existing tool materials.

The wear of cemented tungsten carbide tools while sawing particleboard was investigated by Okumura et al.<sup>12,14</sup> and Sugihara et al.<sup>13</sup> They reported that wear of the cutting edge occurs primarily on the clearance face, with visible striations and grooves developing along the cutting direction. Scanning electron microscopic (SEM) examination of the worn surfaces revealed that wear of the cutting edge occurred by preferential removal of the cobalt binder from between the tungsten carbide grains. Such removal caused the tungsten carbide grains on the surface of the tool to be loosely held in the composite matrix and subsequently be mechanically removed from the edge. These authors pointed out that the width of the wear land on the back of the tool was proportional to the normal force component and suggested that friction on the back surface was responsible for tool wear while sawing particleboard. Sugihara et al.<sup>13</sup> reported that fine-grained saw tips wore more than coarse-grained tips. This finding, however, was not supported by the work of Okumura et al.,<sup>14</sup> who reported that coarse-grained saw tips wore more than fine-grained tips.

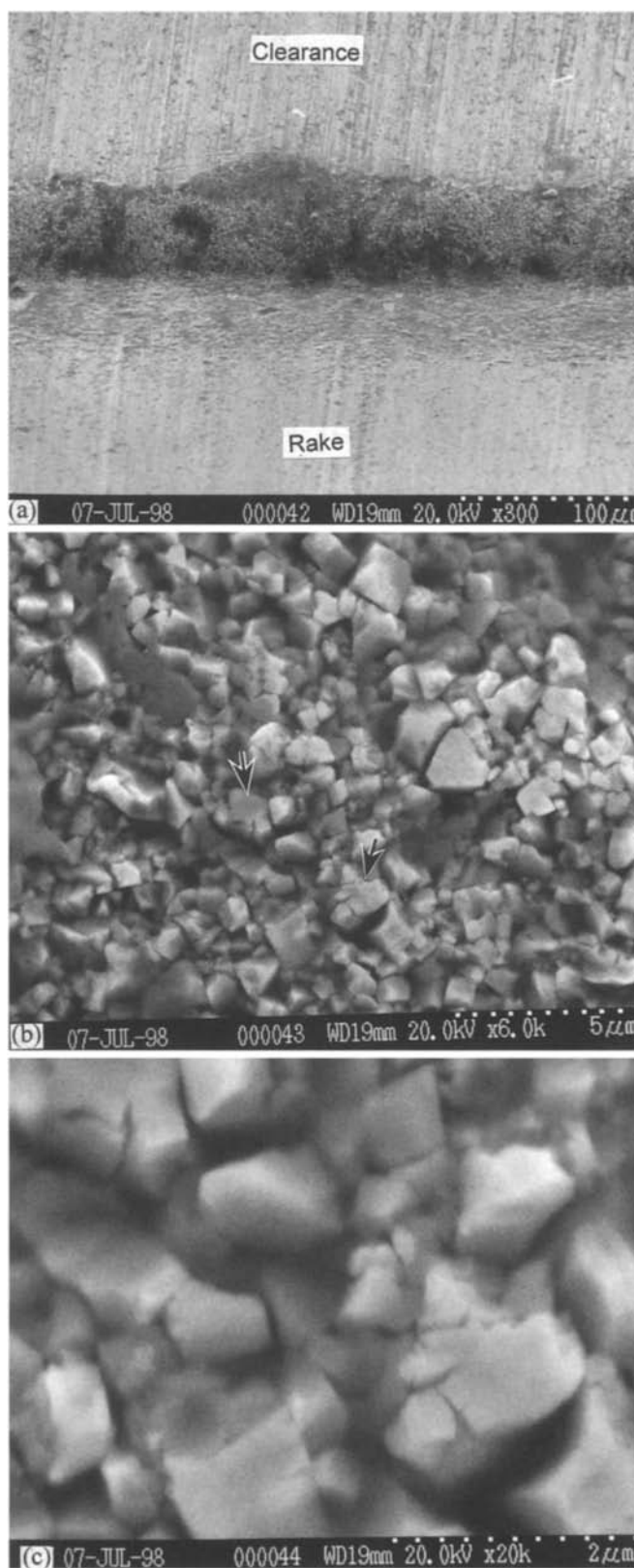
Salje<sup>54</sup> investigated the performance of five grades of cemented tungsten carbides in the peripheral milling of particleboard. The grain size of the tungsten carbide tools was varied from 2.0 to 0.5 µm, and their hardness was varied from 1750 to 2350 HV<sub>10</sub>. It was reported in this work that wear resistance was mainly dependent on hardness, and that a good correlation existed between tool life and hardness for all grades tested. This finding was confirmed by the results of Bansyoya et al.,<sup>16</sup> Sheikh-Ahmad and Bailey,<sup>18</sup> and Sheikh-Ahmad et al.,<sup>24</sup> who used several grades of tungsten carbide tools for machine boring MDF and particleboard and for the continuous and interrupted cutting of particleboard and MDF, respectively. Figure 2 shows experimental data compiled from the previous work and demonstrates the inverse relation between tool hardness and tool wear. It was also noted in this work that wear of the



**Fig. 2.** Variation of tool wear with bulk hardness for various tungsten carbide grades used when machining particleboard and fiberboard. Letters indicate tungsten carbide grain size: C, coarse; M, medium; F, fine; X, extra fine; U, ultrafine. MDF, medium-density fiberboard; PB, particleboard; superscript numbers, references cited in text

carbide cutting tool takes place primarily on the clearance face, and that the amount of tool wear is proportional to the normal force component. The wear surfaces were also reported to consist of carbide grains standing in relief with the cobalt binder removed. Evidence of cracking and microfracture of the carbide grains were also apparent.<sup>18</sup> These observations lead to the conclusion that mechanical removal of the metal binder is the most likely cause of cutting edge degradation while machining particleboard and fiberboard. Typical wear surfaces of a cemented carbide tool used for machining particleboard are shown in Fig. 3.

Stewart et al.<sup>15</sup> performed cutting experiments on MDF disks on a lathe using WC-6Co tools. Auger electron spectroscopy (AES) was used to identify the elemental constituents of the residues on the surface of the tool at the cutting edge, at a middle region adjacent to the cutting edge, and at a darkened organic layer on the trailing edge. Results of the AES analysis of a tool used to machine MDF at 3300 rpm showed higher than nominal cobalt peaks in the middle region, which was interpreted as cobalt buildup in this region. It was postulated that this buildup partially resulted from the reduction of tungsten carbide by decarburization followed by oxidation of tungsten. The lower cobalt peak at the cutting edge was attributed to lower cobalt concentration, presumably because of localized melting, plastic flow, or oxidation/corrosion. Examination of the worn tool by SEM showed depressions and pits near the cutting edge, which were interpreted as arising from oxidation/corrosion of the tool material by thermal decomposition components of MDF at high temperatures. The presence of sulfur, chlorine, calcium, and carbon was detected on the wear surface by AES and was attributed to thermal decomposition of MDF at high temperatures. Additional cutting tests at 550 rpm showed that the cutting tool wore by removal of the cobalt binder from around the tungsten carbide grains.<sup>15</sup> It was proposed that temperatures of the order of 800°–850°C



**Fig. 3.** Scanning electron microscopy (SEM) photomicrographs showing the wear features of a cemented tungsten carbide (WC) cutting edge after machining particleboard. Wear takes place primarily on the clearance face (a), and the worn surface reveals the presence of WC grains standing in relief (b) with cobalt binder removed and shallow depressions once occupied by WC grains. Arrows indicate the presence of transgranular cracks in the WC grains. (c) Same grains at high magnification

existed at the edge, and that hot corrosion is the main mechanism responsible for cobalt removal at this low cutting speed. In later work Reid et al.<sup>43</sup> subjected WC-6Co blanks to the rubbing action of MDF disks while heating the blank at 325°C. EDS was then used to identify the elemental constituents of the residues on the rubbed surface of the tungsten carbide blank. A temperature of 325°C was selected because wood decomposition is maximum at this temperature.<sup>55,56</sup> EDS analysis after 40h of rubbing showed high cobalt concentrations at the edge and middle regions of the tool and high sulfur concentration at the middle region. Cobalt and sulfur buildup also occurred on tools rubbed for 19h against the MDF disk at temperatures as low as 200°C. It was concluded from this work that wear of the cutting edge occurred mainly because of the corrosive reaction of sulfur with cobalt, which resulted in weakening the binder and the loss of carbide grains by mechanical action. No explanation was given as to how sulfur corrosion would cause cobalt buildup, not depletion, at the cutting edge.

Porankiewicz et al.<sup>50</sup> and Porankiewicz and Wagner<sup>51</sup> used XPS and AES to identify the chemical composition and elemental constituents of the residues on WC-6Co cutting tools after peripheral milling of MCPB and MDF. XPS results for the tool used for cutting MCPB showed the presence of cobalt oxides  $\text{Co}_2\text{O}_3$  on the worn part of the cutting edge and both metallic Co and the oxide CoO on the unworn part. Neither WC nor its oxides were detected on the worn or unworn parts of the edge. AES analysis of this tool showed that similar concentrations of WC were detected on the worn and unworn parts of the edge, and that cobalt concentration for the worn part was higher than that for the unworn part after sputtering the surface (cleaning) by ion bombardment for 70min. No explanation was given as to what caused this higher cobalt concentration on the worn part of the tool. XPS results for the tool used for cutting MDF showed the presence of WC on the worn edge and both CoO and WC on the unworn edge. Again, no tungsten oxides were found on the worn or unused parts of the edge. AES analysis of this tool showed that after sputtering for 60min, the WC concentration was higher in the unworn part than in the worn part and that no cobalt was found on the worn part. The absence of cobalt in the latter case was interpreted to be a result of cobalt erosion from the cutting edge. Neither XPS nor AES detected the presence of significant sulfur or chlorine deposits on the cutting edge of the worn tool after machining MCPB and MDF. This is in contrast to the findings of Stewart et al.<sup>15</sup> and Reid et al.,<sup>43</sup> discussed earlier, where high concentrations of sulfur resulting from thermal decomposition of MDF were detected on the surface of the worn tool. It was concluded from this work that oxidation of cobalt is the major wearing process. Based on the results of DTA reported earlier,<sup>51</sup> it was concluded that the temperature at the cutting edge while machining does not exceed 490°C.

It must be pointed out here that some of the apparent discrepancies in the experimental results reported above may be related to the nature of the microanalysis techniques used. It is known that AES and XPS can provide

useful surface microanalyses only to a depth of a few nanometers,<sup>57,58</sup> and that surface matrix effects, particularly contamination, influence the accuracy of the results of these analytical tools. More often the combination of ion beam etching and AES or XPS is used to construct an in-depth profile of the distribution of elemental constituents in the sample. On the other hand, AES and EDS analyses can provide information only on the elemental constituents of the surface analyzed; no information can be provided regarding the chemical state of these elements. Thus, when an element peak shows in the Auger electron or dispersive energy spectrum, it is not known whether this element is in a pure metallic or an oxidized form. This is not a limiting feature of XPS, however, because the emitted photoelectrons are sensitive to the chemical state (bonding) of the atom; hence, it can be used for identification of chemical compounds on the surface of the sample.

The effect on tool wear of adding corrosion resistance elements to the cobalt binder of the WC-Co alloy has also been reported in the literature.<sup>18,43,59</sup> It was noted that adding alloying elements such as chromium, nickel, and molybdenum to the binder metal did not bring about any significant improvements in wear resistance.<sup>18,43</sup> To the contrary, the performance of some alloyed grades was degraded by the addition of alloying elements,<sup>18</sup> despite the fact that these alloying elements have the effect of increasing the hardness and oxidation resistance of the cobalt binder.<sup>45,46,60</sup> Because the binder phase in these alloys is harder, it is more resistant to extrusion and microabrasion than pure cobalt. It is possible that the increase in hardness and decrease in ductility of these alloys caused failure during the binder phase by brittle fracture, rather than by extrusion. This was indicated by the presence of larger-than-grain-size aggregates of the tool material removed from the wear surface.<sup>18</sup>

Porankiewicz<sup>59</sup> investigated the effects of workpiece and cemented carbide tool materials on tool wear during the peripheral milling of particleboard. Six types of melamine-coated and uncoated particleboard and eight types of micrograin-cemented carbides were used in this study. A two-dimensional correlation analysis was utilized to quantify the effect of workpiece and tool material variables on tool wear. Porankiewicz reported that high correlation coefficients existed between tool wear and the mineral content of the particleboard (0.84), the average size of the mineral particles (0.73), and the high temperature corrosivity of the workpiece toward cobalt as measured by weight changes during DTA (0.43). The high correlation coefficient associated with the mineral content of the particleboard implies the significance of mechanical wear by micro-abrasion. Increasing the vanadium content, coercion coefficient of the carbide grains, and tool hardness were shown to decrease tool wear, whereas increasing the nickel and chromium content increased tool wear. The negative effects of nickel and chromium additions are somewhat in disagreement with observed oxidation kinetics reported in the literature.<sup>45,46</sup>

Stewart<sup>61</sup> reported that boriding WC-6Co alloy by thermal diffusion of boron into the surface layer resulted in less tool wear while machining MDF. This improvement was



attributed to the increase in hardness and oxidation resistance of the cobalt binder, which was caused by the formation of cobalt borides at the surface of the tool. Similar findings were reported by Mueller<sup>62</sup> in the case of boron ion-implanted cemented carbide dental burs. An apparent disadvantage of the boriding treatment by thermal diffusion and ion implantation is that the implanted depth is often too shallow to maintain wear resistance for a long time. In addition, any subsequent tool resharpener would result in removing the implanted layer and uncovering the untreated substrate.

## Discussion

To elucidate the possible mechanisms responsible for tool wear while machining particleboard and fiberboard many researchers have conducted actual or simulated cutting experiments and examined the worn tool using optical and SEM.<sup>12-18</sup> Other researchers utilized advanced microanalysis techniques to examine the chemical composition of the wear surface after machining.<sup>43,48-51</sup> One common problem associated with both types of study is that they are based on postmortem or indirect observations of the wear process and thus may not be suitable for positively identifying specific wear mechanisms or for providing quantitative data. Therefore, the body of work conducted to date provides somewhat conflicting theories as to the possible wear mechanisms during machining particleboard and fiberboard.

Based on observations of the microstructure of the worn surfaces using SEM<sup>12-18</sup> there is a general consensus that wear of the cutting edge occurs primarily by preferential removal of the binder metal, which is mostly cobalt, from between the tungsten carbide grains. This preferential removal of the binder phase causes the tungsten carbide grains on the surface of the tool to loosen and subsequently be removed from the edge by fracture and dislodgment. SEM photomicrographs often show tungsten carbide grains standing in relief on the wear surface as well as cavities once occupied by carbide grains that have been removed. There is also clear evidence of fragmentation of the WC grains, especially for grades with medium- and fine-grain sizes.<sup>18</sup> Similarities in the microstructural appearance of the wear surfaces for the various carbide grades investigated suggest that removal of the binder metal is the controlling mechanism of wear in all cases. On the other hand, there is no evidence of wear (oxidation/corrosion pits, rounding) on the tungsten carbide grains themselves, and they appear to have retained their original angular sharp appearance.<sup>12-14,18</sup> Oxidation kinetics studies have also shown that oxidation of WC-Co alloys becomes significant only at temperatures above 700°C,<sup>40,44</sup> and that vaporization of the WO<sub>3</sub> oxide becomes significant only at temperatures above 1000°C.<sup>60,63</sup> The highest temperature measured during wood cutting was 550°C, as shown in Table 1, and no tungsten oxides were detected on the surface of the worn tools used for machining particleboard.<sup>50,51</sup> Hence, oxidation of tungsten seems to be an unlikely wear mechanism.

Identification of the wear mechanism(s) responsible for preferential removal of the binder metal during wood cutting is not an easy task due to the complexity of the problem. For many cutting processes, conditions are such that several wear mechanisms can occur simultaneously. In addition, synergistic interaction between these mechanisms is likely. Therefore, separating the individual wear mechanisms during a cutting process is rather complicated.

Evidently, the bulk of the work conducted to date points to two wear processes as possibly being responsible for removal of the binder metal. These processes are chemical wear by high-temperature corrosion<sup>15,43,48-52</sup> and mechanical wear by binder extrusion, microabrasion, and fracture.<sup>12,13,16,18,54</sup> Although conditions at the cutting edge may be such that both wear mechanisms are operating at the same time; it is most likely that only one mechanism takes a dominant role in the wear process and becomes rate controlling. In this section we take a closer look at the premises behind the assumptions made in the work reviewed earlier and examine them in view of the observed high-temperature reaction kinetics of WC-Co alloys in air or in the presence of reconstituted wood products as described above.

There is some evidence in the literature that conditions at the cutting edge during wood machining are favorable for oxidation of the cobalt binder to occur. Some of the cutting tool temperatures reported in Table 1 are indeed high enough for cobalt to oxidize,<sup>64</sup> and microanalysis of the worn tool did indicate the presence of cobalt oxides on the wear surface and in wood decomposition residues behind the wear area.<sup>50,51</sup> The relative motion between the workpiece and the cutting tool would facilitate removal of cobalt oxides from the cutting edge, continuously exposing a fresh surface, and hence accelerate the oxidation rate. As a result, the tungsten carbide grains are left with little support and are subsequently removed from the edge by mechanical action.

A major deficiency in the high-temperature oxidation/corrosion theory is the apparent lack of quantitative measures of the oxidation rate of the cobalt binder and how much it contributes to the process of cobalt removal from between the carbide grains. The presence of cobalt oxides on the wear surface as detected by microanalysis techniques cannot alone provide information regarding the rate of oxidation. It is also not clear from the findings of the work conducted to date whether oxidation of the cobalt binder takes place by reaction with oxygen from air or by reaction with thermal decomposition components of the workpiece. XPS analysis of the worn tool did not indicate the presence of cobalt compounds other than oxides,<sup>51,52</sup> although high concentrations of sulfur, chlorine, and calcium were present.<sup>15,43,48</sup> Furthermore, results from comparative wear experiments on WC-Co grades with alloying elements added to the cobalt binder did not show any significant advantages associated with alloying,<sup>18,43,59</sup> which suggests that the role of oxidation/corrosion is secondary.

Mechanical interaction between the tool and the workpiece is an important factor in determining the type of wear processes that are possible during machining. There is strong evidence in the work reviewed that wear of the WC-



based alloys is inversely proportional to their bulk hardness,<sup>14,16,18,24,54,59</sup> as shown in Fig. 2. This indicates that some form of abrasive wear was present under the conditions of the work conducted. It is noted that hardness is a measure of the resistance to indentation by an indenter that is several times larger than the WC grain size. Therefore, hardness represents an average property of the material, which is often related to plastic deformation and wear.<sup>65</sup> The classical theory of abrasive wear assumes that material removal takes place by penetration of harder abrasive particles into a softer body and then cutting by plastic flow to form grooves in the surface of the softer body. The wear rate is proportional to the normal load and is inversely proportional to bulk hardness for most metals when abrasive wear is the dominant mechanism of material removal.<sup>66</sup> Abrasive wear by indentation and grooving, however, is not likely to occur in machining wood-based products because the latter are much softer than the cemented carbide tools and are not able to penetrate the harder tool material.

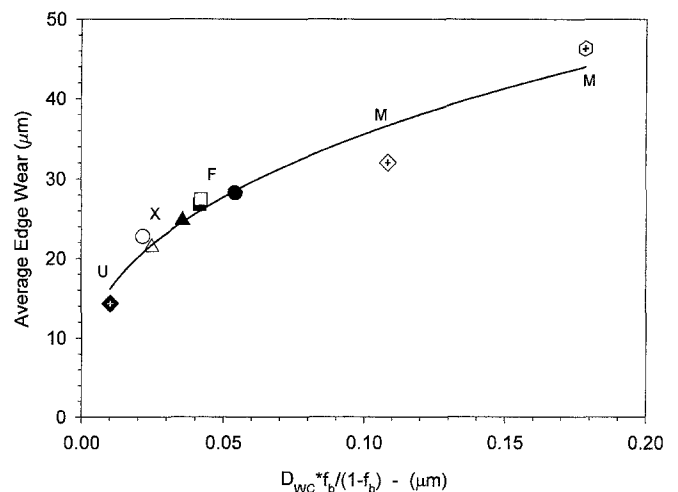
Abrasion of cemented carbide tools while machining particleboard and fiberboard may occur on a smaller scale than the gross indentation and grooving postulated by the classical theory of abrasion. Material removal by "soft abrasion" has been previously described by Larsen-Basse and Koyanagi,<sup>67</sup> Larsen-Basse and Devani,<sup>68</sup> and Jia and Fischer<sup>69</sup> as the controlling wear mechanism for applications where cemented tungsten carbides are used against softer abrasives such as sandstone and zirconia. According to this mechanism, wear proceeds by removal of the cobalt binder from between the tungsten carbide grains, which is followed by their fragmentation and uprooting. In the work of Sheikh-Ahmad and Bailey<sup>18</sup> it was suggested that wear of the cemented carbide tools while machining particleboard and fiberboard proceeds in a similar manner. First, the binder phase is partly removed from between the tungsten carbide grains by a combination of plastic deformation and microabrasion. This action constitutes the initial and most critical stages of wear. The second stage of wear occurs when sufficient binder has been removed to allow removal of the carbide grains from the surface by mechanical forces. Workpiece materials such as particleboard and fiberboard are inhomogeneous composites consisting of wood particles, wood fiber, and hardened resin. During the machining of these materials high fluctuating forces are generated at the tool-workpiece interface. Under the effect of these fluctuating forces, especially the frictional force, the tungsten carbide grains would oscillate slightly in their position in the WC-binder composite. This, in turn, may result in partial extrusion of the binder to the surface of the cutting tool where it is later removed by the workpiece through mechanical action. In addition, the relative motion of the brittle carbide grains may result in the development of cracks across the grains, which may be followed by fragmentation and removal of parts of or the whole grain from the composite matrix. Such fractured grains were clearly observed on SEM photomicrographs of the worn surface of carbide tools after machining particleboard<sup>18</sup> as shown in Fig. 3. Moreover, particleboard and fiberboard often contain abrasive particles such as sand.<sup>59,70,71</sup> Loose

microfragments of these abrasives at the interface between the tool and workpiece are able to penetrate, under cutting pressure, between the carbide grains and preferentially remove the cobalt binder by microabrasion.

Mechanical properties of the WC composites and the binder phase are strongly dependent on the mean free path in the binder phase.<sup>72</sup> The mean free path during the binder phase is a measure of the thickness of the binder layers between the WC grains, and it describes the distance dislocations can move for plastic deformation to occur (provided the binder phase is free of precipitates). Therefore, tool wear by cobalt extrusion and microabrasion is dependent on the mean free path during the binder phase and the frictional load responsible for the relative movement of the WC grains. It was shown in the work of Sheikh-Ahmad and Bailey<sup>18</sup> that a good correlation exists between the amount of wear and the mean free path during the binder phase for several cemented tungsten carbide alloys tested while machining particleboard, as shown in Fig. 4. A good correlation also existed between the compressive strength of the WC-binder alloys and the amount of wear. Compressive strength is strongly dependent on the weight fraction and hardness of the binder phase, and a correlation between wear and compressive strength further supports the concept of binder removal by extrusion and microabrasion.<sup>18,29</sup> In addition, a good correlation between wear and the normal force, which is proportional to the frictional force on the back of the tool, has also been reported by many investigators.<sup>12,14,18,54</sup> All this further suggests that wear by binder extrusion and microabrasion may be the controlling wear mechanism during the machining of particleboard and fiberboard.

## Conclusions

A review of published work on the wearing processes of cemented tungsten carbides during the machining of



**Fig. 4.** Variation of tool wear with the normalized mean free path of the binder phase for several carbide grades used when machining particleboard.<sup>18</sup>  $D_{WC}$ , WC grain size;  $f_b$ , binder content (wt%). WC grain size letters are as in Fig. 2

particleboard and fiberboard was performed, and the current understanding of the wear phenomenon was evaluated. The major findings of this review are as follows.

1. A large body of the work reviewed indicates that wear takes place by removing the binder phase from between the tungsten carbide grains. Removal of the binder phase eventually leads to removal of the carbide grains by fracture and dislodgment. Wear by brittle fracture was also reported in the case of grades with alloyed binders.

2. Two possible mechanisms of cobalt removal were reported in the literature: chemical wear by oxidation/corrosion and mechanical wear by extrusion, microabrasion, and brittle fracture.

3. The work reviewed indicated a strong correlation between tool wear and tool hardness, tool wear and compressive strength of the tool material, and tool wear and the frictional force on the clearance face of the tool. The work reviewed also indicated the presence of cobalt oxides on the wear surface and a lack of improvement in the performance of carbide grades with oxidation- and corrosion-resistant binders. This suggests that mechanical wear is more significant under the conditions of the work conducted. Synergistic interaction between oxidation/corrosion and mechanical wear is also possible, but this interaction cannot be quantitatively assessed based on the work reviewed.

4. The work reviewed is lacking in terms of quantitative assessment of the oxidation/corrosion rates during actual machining, and fundamental work in this area is needed. Studies that relate the transient nature of cutting tool temperature, the role of thermal decomposition of the workpiece, the role of exposure time, and the possible interactions with mechanical properties of the tool material are desirable.

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## References

- Brookes K (1979) World directory and handbook of hardmetals. Engineers' Digest, London, p 13
- Kirbach E, Chow S (1976) Chemical wear of tungsten carbide cutting tools by Western redcedar. *For Prod J* 26(3):44-48
- Bailey JA, Bayoumi A-M, Stewart JS (1983) Wear of cemented tungsten carbide tools in machining oak. *Wear* 85:69-79
- Bayoumi A-E, Bailey JA, Stewart JS (1983) Comparison of the wear resistance of various grades of cemented carbides that may find application in wood machining. *Wear* 89:185-200
- Bayoumi AE, Bailey JA (1984) An analytical and experimental investigation of the wear of cemented carbide cutting tools in the presence of dilute organic acids. *Wear* 94:29-45
- Bayoumi AE, Bailey JA (1985) Comparison of the wear resistance of selected steels and cemented carbide cutting tool materials in machining wood. *Wear* 105:131-144
- Murase Y (1984) Effect of tool materials on the corrosive wear of wood-cutting tools (in Japanese). *Mokuzai Gakkaishi* 30:47-54
- Kirbach E, Bonac T (1982) Dulling of sawteeth tipped with a stellite and two cobalt-cemented tungsten carbides. *For Prod J* 32(9):42-45
- Mohan GD, Klamecki BE (1981-1982) The susceptibility of wood-cutting tools to corrosive wear. *Wear* 74:85-92
- Fukuda H, Banshoya K, Murase Y (1992) Corrosive wear of wood-cutting tools. I. Effects of tool materials on the corrosive wear of spur machine-bits (in Japanese). *Mokuzai Gakkaishi* 38:764-770
- Fukuda H, Banshoya K, Manatani T, Murase Y (1994) Corrosive wear of woodcutting tools. II. Effects of alloy compositions on the corrosive wear of cemented-carbide bits (in Japanese). *Mokuzai Gakkaishi* 40:687-693
- Okumura S, Sugihara H, Ikeuchi K (1978) Wearing process of tungsten carbide tipped circular saw - interrupted cutting of particleboard with a single saw tooth (in Japanese). *Bull Kyoto Univ For* 50:201-208
- Sugihara H, Okumura S, Haoka M, Ohi T, Makino Y (1979) Wear of tungsten carbide tipped circular saws in cutting particleboard: effect of carbide grain size on wear characteristics. *Wood Sci Technol* 13:283-299
- Okumura S, Sugihara H, Yokoyama Y (1981) Wear of carbide tips in the turning of particleboard (in Japanese). *J Soc Mat Sci* 30:685-690
- Stewart H, Shatynski S, Harbison B, Rabin B (1986) High-temperature corrosion of tungsten carbide from machining medium-density fiberboard. *Carbide Tool J* 18(1):2-7
- Banshoya K, Fukuda H, Mantani T, Murase Y (1995) Wear of cemented carbide bits in machine boring of particleboard and MDF (in Japanese). *Wood Ind* 50:413-417
- Parakash LJ (1995) Application of fine grained tungsten carbide based cemented carbides. *Int J Refract Metals Hard Mater* 13:257-264
- Sheikh-Ahmad JY, Bailey JA (1999) The wear characteristics of some cemented tungsten carbides in machining particleboard. *Wear* 225-229:256-266
- Chardin A (1973) Laboratory studies of temperature distribution on the face of a sawtooth. In: Dost A (ed) Proceedings of the 4th wood machining seminar. Forest Products Laboratory, University of California Berkeley, pp 67-84
- Murase Y, Mori M (1983) On the surface temperature and wear of metal in repeated sliding contact with particleboard. *Mokuzai Gakkaishi* 29:220-226
- Inoue H (1985) Effect of cutting speed and rake angle on knife-edge temperature during 90-0 cutting of wood (in Japanese). *Mokuzai Gakkaishi* 31:454-459
- Okumura S, Kuratsu H, Sugihara H (1987) Tool temperature in machine boring of wood (in Japanese). *Mokuzai Gakkaishi* 33:274-280
- Okumura S, Ishii T, Noguchi M (1993) Temperature of rubbing surfaces between a steel rod and wood and wood composites (in Japanese). *Bull Kyoto Univ For* 65:339-346
- Sheikh-Ahmad J, Lemaster R, Stewart J, Bailey J (1996) Performance of carbide tooling in woodworking applications. Report to the carbide tooling research consortium of the wood machining and tooling research program, North Carolina State University, Raleigh, NC
- Okushima S, Sugihara H, Umemoto M (1969) Temperature of cutter-cusp in wood cutting. *Mokuzai Gakkaishi* 15:197-202
- Okumura S, Sugihara H (1981) Temperature of sawtooth cusp in rubbing of the back face with wood (in Japanese). *Bull Kyoto Univ For* 53:241-247
- Okumura S, Okuda T, Sugihara H (1983) Temperature distribution on the side face of a saw tooth in interrupted cutting. I. Orthogonal cutting. *Mokuzai Gakkaishi* 29:123-130
- Okumura S, Sugihara H, Okuda T (1983) Temperature distribution on the side face of a saw tooth in interrupted cutting. II. Grooving (in Japanese). *Mokuzai Gakkaishi* 29:131-138
- Hayashi K, Suzuki T (1983) Effect of cutting speed on tool wear in the peripheral milling of wood (in Japanese). *Mokuzai Gakkaishi* 29:36-42
- Hayashi K, Oono M, Ito M (1986) Estimation of tool temperature in the neighborhood of the cutting edge in peripheral milling of wood (in Japanese). *Mokuzai Gakkaishi* 32:603-607
- Banshoya K, Fukui T (1987) Tool life in machine boring of wood and wood-based materials. VII. Effect of cutting heat on the tool wear of spur machine-bits (in Japanese). *Mokuzai Gakkaishi* 33:857-864

32. Tsutsumi S, Kato T, Hayashi K (1989) Visualization of temperature distribution near the cutting edge by means of a vacuum deposition of thermoscopic film on matching surface of a split tool. *Mokuzai Gakkaishi* 35:382–384
33. Okushima S, Sugihara H (1972) Temperature distribution analysis of wood cutting tool with differential method (in Japanese). *Bull Kyoto Univ For* 43:328–334
34. Lowen EG, Shaw MC (1954) On the analysis of cutting-tool temperatures. *Trans ASME* 76:217–231
35. Okumura S (1985) A theoretical approach to the cutting edge temperature in interrupted cutting of wood. *Mem Coll Agric Kyoto Univ* 127:29–36
36. Csanady E (1993) Heat transfer and thermal loading in wood cutting tools. In: *Proceedings of the 11<sup>th</sup> international wood machining seminar*. Norwegian Institute of Wood Technology, Oslo, pp 486–494
37. Lewandowski C (1997) Determination of the temperature distribution in wood cutting tools. Masters thesis, North Carolina State University, Raleigh, NC
38. Kieffer R, Kölbl F (1950) *Z Anorg Chem* 262:229; reported in: Schwarzkopf and Kieffer R (1953) *Refractory hard metals*. Macmillan, New York
39. Dawidl W (1940) *Chem Fabrik* 13:133; reported in: Schwarzkopf P, Kieffer R (1953) *Refractory hard metals*, Macmillan, New York
40. Gumnitskii Y, Pelekh M, Givlyud N (1989) Special features of kinetics of high-temperature oxidation of VK8VK alloy. *Soviet Mater Sci* 24:458–463
41. Larikov L, Tishkova T, Tyshkevich V, Shmatko O (1990) Study of the kinetics of oxidation of W-Co and WC-Co alloys. *Protect Metals* 25:524–526
42. Lofaj F, Kaganovskii Y (1995) Kinetics of WC-Co oxidation accompanied by swelling. *J Mater Sci* 30:1811–1817
43. Reid A, Stewart H, Rapp R (1991) High-temperature reactions of tungsten carbide-cobalt tool material with MDF. *For Prod J* 41(11/12):12–18
44. Basu SN, Sarin VK (1996) Oxidation behavior of WC-Co. *Mater Sci Eng A* 209:206–222
45. Bhaumik S, Balasubramanian R, Upadhyaya G, Vaidya M (1992) Oxidation behaviour of hard and hard binder phase modified WC-10Co cemented carbides. *J Mater Sci Lett* 11:1457–1459
46. Oakes J (1987) Effect of Cr and Mo additions to the binder phase of cemented carbides used for rod mill rolls. *Metal Powder Rep* 42:492–499
47. Voitovich VB, Sverdel VV, Voitovich RF, Golovko EI (1996) Oxidation of WC-Co, WC-Ni and WC-Co-Ni hard metals in the temperature range 500–800°C. *Int J Refract Hard Mater* 14:289–295
48. Padilla M, Rapp R, Stewart H (1991) High temperature oxidation of tungsten carbide-cobalt composites in the presence of MDF. *For Prod J* 41(10):31–34
49. Porankiewicz B (1992) Does chemical corrosion of carbide cutting edges occur when milling melamine coated particle board. Presented at the seminar of the Faculty of Wood Technology, Agriculture University of Pozan, Poland. Cited in Dziembaj et al.<sup>52</sup>
50. Porankiewicz B, Ziomek-Moroz M, Wagner K (1995) Study of wearing process of cemented carbide cutting edge when milling secondary wood products. In: *Proceedings of the 12th international wood machining seminar*, Kyoto University, Japan, pp 272–281
51. Porankiewicz B, Wagner K (1995) The study of high temperature corrosion of cemented carbide cutting edge after coated particle board processing using advanced surface analyzing methods. In: *Proceedings of the 13th international wood machining seminar*, Vancouver, Canada, pp 651–657
52. Dziembaj R, Lachman O, Porankiewicz B (1993) Chemical corrosion of carbide cutting edge when milling melamine coated particle board. In: *Proceedings of the 11th international wood machining seminar*, Norwegian Institute of Technology, pp 137–145
53. Gallagher PK (1991) Thermoanalytical methods. In: Cahn RW, Haasen P, Kramer EJ (eds) *Materials science and technology: a comprehensive treatment*, Vol 2A:pt. I, VCH, New York, p 492
54. Salje E (1988) Milling of particleboard with high hard cutting materials. In: Lemaster R (ed) *Proceedings of the 9th international wood machining seminar*, Forest Products Laboratory, University of California Berkeley, pp 211–228
55. Brown HP, Panshin AJ, Forsaith GC (1952) *Textbook of wood technology*. McGraw Hill, New York, p 755
56. Beal FC, Eickner HW (1968) Thermal degradation of wood components: a review of the literature. FPL-130. USDA Forest Service, Forest Products Laboratory Madison, WI, USA
57. Goldstein J, Newbury D, Echlin P, Joy D, Fiori C, Lifshin E (1984) *Scanning electron microscopy and X-ray microanalysis*. Plenum Press, New York
58. Eberhart JP (1991) *Structural and chemical analysis of materials*. Wiley, New York
59. Porankiewicz B (1997) Variation in composition of micro-grain cemented carbide and its impact on cutting edge wear during particleboard machining. In: *Proceedings of the 13th international wood Machining Seminar*, Vancouver, Canada, pp 791–799
60. Kubaschewski O, Hopkins B (1962) *Oxidation of metals and alloys*, Butterworths, London
61. Stewart H (1987) Borided tungsten carbide reduces tool wear during machining of MDF. *For Prod J* 37(7/8):35–38
62. Mueller HJ (1993) Cutting performance of boron implanted cemented carbide dental burs. *Microstruct Sci* 20:485–498.
63. Kang S, Fromm E (1981) Reactions of molybdenum and tungsten carbides with oxygen at high temperatures. *Met Trans* 12A:1993–1998
64. Young RS (1948) *Cobalt*. Reinhold, New York, pp 57–65
65. American Society of Metals (1985) *Hardness testing*. In: *Metals handbook*, vol 9. ASM, Metals Park, OH, USA, pp 69–113
66. Rabinowics E (1965) *Friction and wear of materials*. Wiley, New York, p 167
67. Larsen-Basse J, Koyanagi ET (1979) Abrasion of WC-Co alloys by quartz. *J Lub Technol* 101:208–211
68. Larsen-Basse J, Devani N (1986) Binder extrusion as a controlling mechanism in abrasion of WC-Co cemented carbides. In: Almond E, Brooks C, Warren R (eds) *Science of hard metals*. Adam Higler, Boston, pp 883–895
69. Jia K, Fischer TE (1996) Abrasion resistance of nanostructured and conventional cemented carbides. *Wear* 200:206–214
70. Porankiewicz B, Gronlund A (1991) Tool wear – influencing factors. In: Lemaster R (ed) *Proceedings of the 10th international wood machining seminar*, Forest Products Laboratory, University of California Berkeley, pp 220–229
71. Huber H (1985) Tool wear influences by the contents of particle-board. In: Lemaster R (ed) *Proceedings of the 8th international wood machining seminar*, Forest Products Laboratory, University of California Berkeley, pp 72–85
72. Exner HE, Gurland J (1970) A review of parameters influencing some mechanical properties of tungsten carbide-cobalt alloys. *Powder Metal* 13:13–31